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Naval Surface Warfare Center
Carderock Division
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Ship Systems Integration & Design Department
Technical Report

Very Versatile Vessel

By

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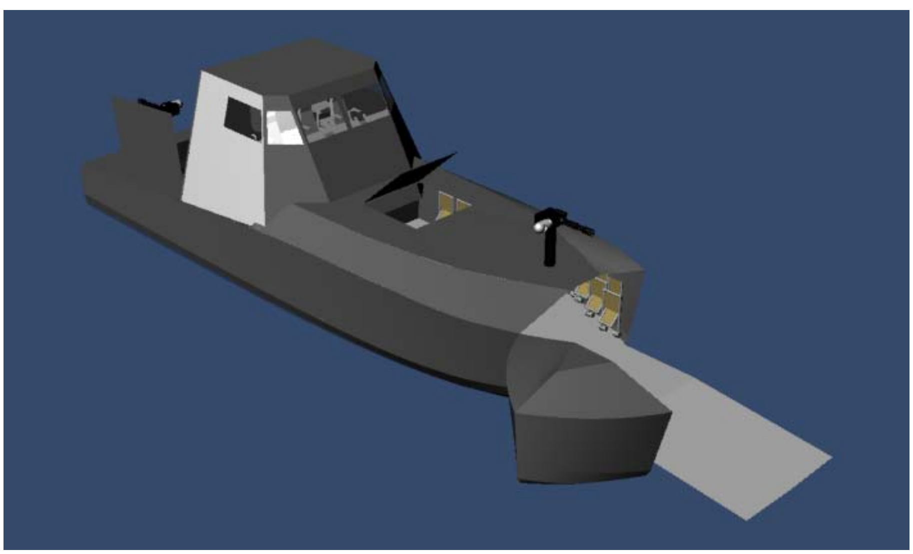

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Seeking to expand the operational capabilities of its amphibious platforms, the United States Navy has suggested the addition of a dual purpose littoral/riverine patrol craft capable of significant personnel and cargo insertion. Operations from amphibious platforms are typically limited to air cushion (LCAC) and displacement landing craft (LCU). These support craft have significant personnel lift capabilities, but they are limited to operation from within the well decks of the amphibious ships. Additionally, neither craft possesses the necessary characteristics for patrol and interdiction missions.

This paper suggests a preliminary design for a "Very Versatile Vessel" (VVV) capable of both davit and well dock deployment, with the ability to support amphibious and riverine operation. This report will address the operational and technical aspects of this design requiring additional investigation. .

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Abstract

Seeking to expand the operational capabilities of its amphibious platforms, the United States Navy has suggested the addition of a dual purpose littoral/riverine patrol craft capable of significant personnel and cargo insertion. Operations from amphibious platforms are typically limited to air cushion (LCAC) and displacement landing craft (LCU). These support craft have significant personnel lift capabilities, but they are limited to operation from within the well decks of the amphibious ships. Additionally, neither craft possesses the necessary characteristics for patrol and interdiction missions.

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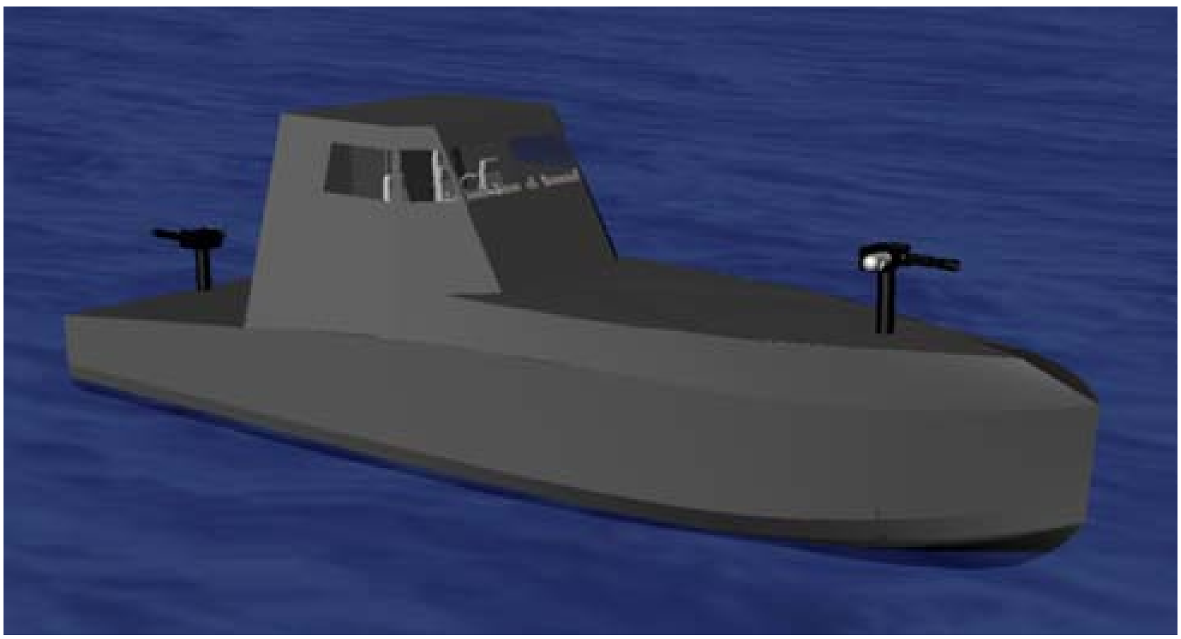

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This report is the culmination of work conducted by three students participating in the National Research Enterprise Intern Program sponsored by the Office of Naval Research. This 10 week summer program provides an opportunity for students to contribute in research at a Department of Navy laboratory. The program aims to encourage careers in science and engineering, to supplement education via mentoring and participation in research, and to increase awareness of Navy research and technology efforts leading to future employment.

At the Naval Surface Warfare Center Carderock Division, the single largest employer of summer interns is the Center for Innovation in Ship Design (CISD), part of the Ship Systems Integration and Design Department. The intern program is one method of student outreach leading to the development of future ship designers.

The design team would also like to thank the following people. Their experience and knowledge helped make this project a success.

Ryan Mortimer	LCDR Mark Read
Dr. Colen Kennell	G. Robert Lamb
Steven Ouimette	John Offutt
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1. Introduction

This project seeks to integrate the key features of landing and littoral/riverine patrol craft into a single multi-mission capable design concept. These craft have fundamentally different and often conflicting characteristics: patrol vessels display speed, range, and stealth while shallow draft and large payload capabilities are necessary for effective landing craft. Davit restrictions on size and weight further complicate the tradeoffs between these conflicting vessel types. Rigid-hull inflatable boats (RHIB) are the United States Navy's closest approximation to these design requirements, but they have limited personnel/cargo lift capabilities and generally lack ballistic protection.

The US Navy's littoral warfare capabilities would benefit immensely from a vessel capable of inserting a full USMC rifle platoon of 43 soldiers or equivalent weight in cargo. Design requirements for such a vessel would require displacement less than 26 metric tons and overall footprint less than 4.5m by 16m to meet davit restrictions. The vessel should sprint at a speed of 35 knots and cruise at 18 knots, be fully operable in Sea State 4, and insert cargo or personnel through the surf to a variety of beach conditions. A vessel satisfying these requirements would need to be very versatile; hence the "Very Versatile Vessel" (VVV).

2. Mission

The Very Versatile Vessel (VVV) is a multi-mission craft capable of the following roles:

- Riverine and littoral patrol operations
- Littoral interception of hostile targets
- Personnel and cargo delivery from LPD 17 class ship to shore through the surf zone
- Insertion of light infantry forces

Requirements and Restrictions

The wide, diverse set of requirements placed significant restrictions on the craft design. A comprehensive listing can be found in Appendix A, but a summary of the driving design factors is provided in Table 1.

Davit Restrictions	Dimensions no greater than 16m by 4.5m and weight no greater than 26 metric tons
Dock	Operate from the well deck of an LPD-17
Speed	35 knots unloaded, 25 knots loaded
Force Projection	1 USMC platoon with full combat gear
Sea State	SS-4 Operations, SS-5 Survival
Range/Endurance	300 nm at a cruise speed of 18 knots
Beaching	Navigate a beach with 1:120 gradient
Cargo	2 tons cargo alternative
Firepower	2 Miniguns with 360º coverage and -10º to 50º elevation
Protection	Withstand small arms fire above waterline
Detectability	Minimize magnetic and visual signature

Table 1: Summary of Requirements

Analysis of Requirements

Upon review of the requirements, operability from the davits was deemed to be most restrictive since it dictated maximum vessel dimensions and displacement. The weight limit of 26 metric tons was interpreted as a fully loaded weight to ensure speed and simplicity of vessel loading from the ship.

The USMC "light platoon" was assumed to be a standard Marine rifle platoon of 43 soldiers in order to optimize force projection and avoid interference with missions of existing craft [1]. The amphibious assault force was judged to benefit most if the VVV were designed to maximize personnel lift capability. This requirement drove the primary vessel space requirement and therefore the eventual hull form selection.

The 1:120 gradient beaching requirement provided a worst-case scenario for operating environments. This gradient was assumed to be a constant upward slope to the shore without obstacles. Research uncovered a considerably steeper average beach slope [2]; careful mission planning would likely enable selection of more optimal beaches. The design beach gradient influenced propulsor choice, hull shape, and the design draft. A maximum draft limit of 1m was imposed on the design to ensure the platoon would not unload into deeper than waist-high water. A draft of 0.60m would place water at knee height, while a draft of about 0.75m would place water at mid-thigh [3].

The requirement for 300 nm range at cruise speed of 18 knots was taken to be a distance requirement rather than an operation time requirement when eventual design factors drove the cruise speed upward.

Minimization of aural signature was an objective, as vessel-produced sound was decided to be a significant inhibitor to stealth in riverine environments.

Weight and size limitations provided motivation to utilize space as efficiently as possible. This required innovative design and research in different areas including lightweight materials, space arrangement, shipboard systems and integration of calculated data.

Additional Mission Profiles

A number of riverine mission profiles were identified [4]. The VVV is primarily designed for troop transport/insertion/extraction, cargo and logistics support, security patrol/convoy escort/fire support, and visit/board/search/seizure missions.

The VVV would be capable of undertaking several additional riverine missions with slight modification. Implementation of a modular cargo area and some added equipment would enable variants of the VVV to conduct the further mission profiles.

Range, FLIR cameras, and integrated communications capabilities dispose the vessel toward intelligence, surveillance, and reconnaissance missions. Full mission requirements might also demand interoperability with unmanned vehicles (UAV, UUV, and USV) or mission-specific modules.

The craft’s small draft and design for a wide range of operating environments lend the VVV to hydrographic survey support missions also. Mission-specific equipment would provide the necessary technology.

Joint command and control missions would require a workspace for intelligence processing, outfitted in place of the current cargo and personnel transport section. This additional hardware would demand a more robust electrical power and cooling system.

Engagement in search and rescue or humanitarian support/disaster relief missions would require an emergency medical module to be fully capable. Such a module would certainly fit in the VVV’s current cargo compartment.

3. Concept of Operations (CONOPS)

The VVV is designed for an endurance of three days and a range of 300 nm, forcing dependence upon another ship or home port for continued operation. In a Sea Base, the missions of the VVV could initially be conducted from an LPD or other amphibious platform and, as such, the vessel has multiple options for launch and recovery (L/R).

Vessel size and weight were limited with consideration for reasonable davit capacities, though strengthening or modification of current LPD Davits may be necessary to support VVV operations. These davit restrictions ensured that multiple craft could be stowed in an amphibious well deck. Deployment from davits would be preferred for launch and recovery of a single VVV.

Hoisting slings located near the stern and just forward of midships provide stability during launch or recovery from davit. Following successful deployment into the seaway, operations could be conducted through Sea State 4. Configuration and deployment of the VVV will vary depending on the mission being conducted and the host ship.

Troop Transport/Insertion/Extraction

Research on the seating layout of the Chinook CH-47 helicopter and Amphibious Assault Vehicle (AAV) provided a benchmark for the necessary size of the cargo compartment. A small margin was added to increase troop comfort in a seaway. Efficient organization of cargo space verified that the VVV could accommodate a 43 man USMC Rifle Platoon.

During troop transport/insertion/extraction missions, the cargo area of the VVV would be configured to hold a maximum of 42 seats. As pictured in Figure 1, the troop transport would be arranged with 22 seats attached to the hull, facing inward and 20 seats mounted in the center of the cargo area, back-to-back. A 43rd seat for the platoon commander would be installed in the pilothouse for mission logistics and awareness

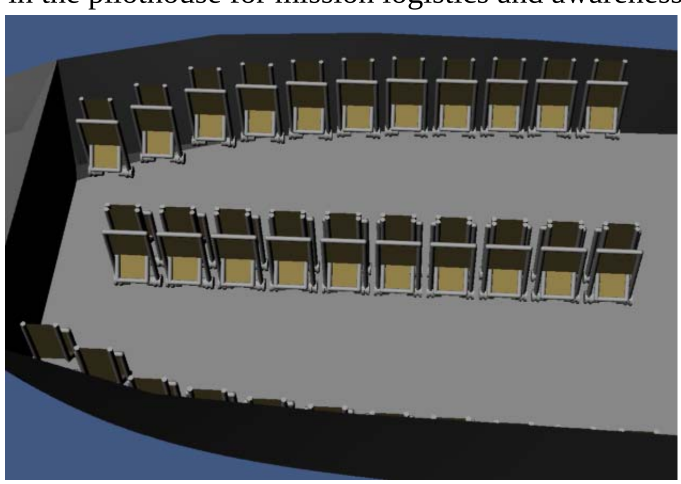

Figure 1: Seating Arrangement

Troops would load onto the VVV onboard the amphibious platform and the vessel would be launched from the well deck or davit. The vessel would then transit to the area of operations and approach the beach. As the vessel approaches the landing zone, troops and operators would ready the bow gate. After the bow opens, hydraulics would extend a ramp from under the cargo deck and lower the forward end to allow rapid ingress/egress for the troops. A hatch in the top deck is included in the event of bow system failure. When personnel insertion is complete, the VVV would self-extract with its waterjets and return to the home platform or conduct the remainder of its mission.

Cargo Systems and Logistics Support

The cargo hold configuration for cargo and logistics support missions would be slightly different. The 22 side seats would still be present, though folded flush against the inner hull when not in use. The center seats, however, would be detached from the cargo deck and left aboard the host platform or possibly placed in the aft storage area.

The VVV could carry a variety of cargo loads, assuming that it fits within the dimensions of the hold and does not affect integrity or stability of the vessel. The team assumed most cargo would be loaded in pallet form. The hold can carry three to four pallets. The design team considered the transport of MREs, the projected least dense cargo, to regulate the size of the cargo systems. Pallets of water and ammo, the densest cargo, provided a reasonable weight limit for the cargo systems. Machinery and electronics were considered as a final possibility. A cargo support system that acts quickly and dependably in a variety of environments and weather conditions is essential to the VVV.

The transport payload could be loaded in different configurations depending on the type of cargo. Cargo in pallet form would be loaded onto a “hover pallet” while other types of cargo could be secured directly to the deck floor. A sample configuration with a hover pallet is pictured in Figure 2.

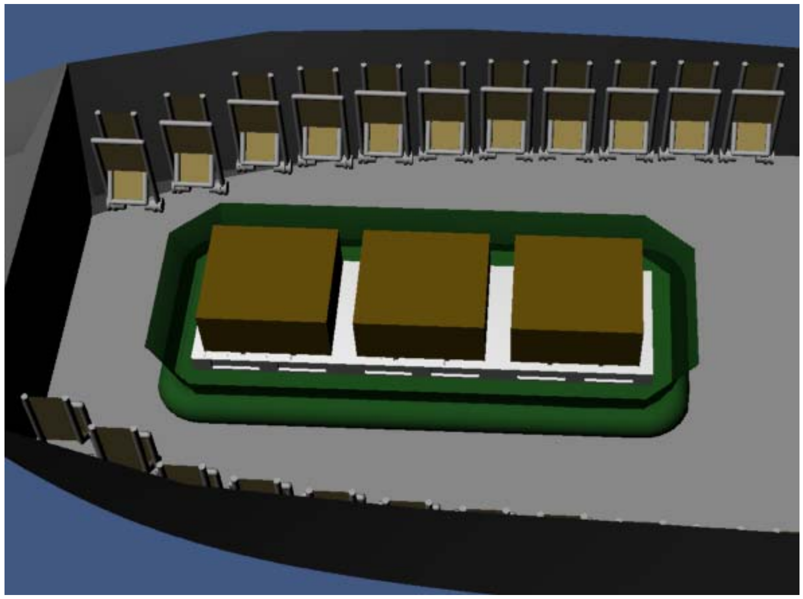

Figure 2: Seating with Cargo

Hover Pallet

The hover pallet is a self-driven air cushion platform with blowers to provide lift. It is designed so that a small crew complement can rapidly transport large quantities of cargo over varied surfaces. Examples of this technology currently exist in large scale hover barges used in various applications around the globe. An example of a more relevant application is shown in Figure 3: the SkimaBarrow formerly produced by Skima Hovercraft Limited [5].

Figure 3: Skima Hovercraft Ltd's "SkimaBarrow 250"

In use, the loaded hover pallet would be inflated onboard the VVV and moved out the bow and down the bow ramp. The hover pallet would be attached to the VVV

via two ropes or cables which could be used to control descent over the ramp and provide a means of recovery. Two crew could push or pull the platform to shore and then either break the cargo into man-sized loads or detach the hover pallet from the vessel and leave it behind.

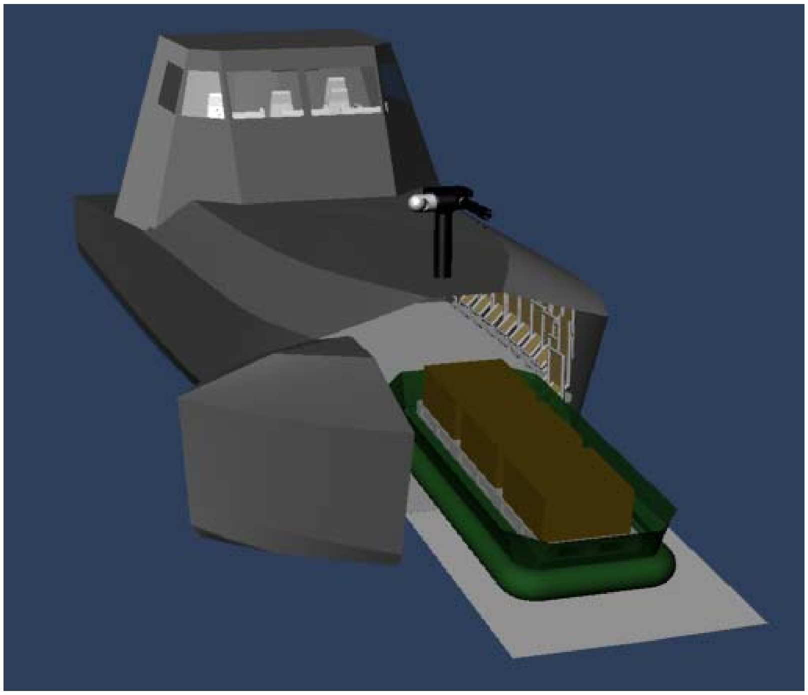

Figure 4: Hover Pallet Being Deployed

Security Patrol, Convoy Escort, Fire Support

The VVV would not require any reconfiguration in order to conduct basic patrol, escort, and fire support operations. However, the cargo area could be outfitted with equipment for long-term missions such as additional fuel tanks or extra ammunition and food stores. The option to be deployed from amphibious ships like the LPD or to operate from friendly ports would allow for mission flexibility where the VVV could be launched shipside and resupplied portside.

Armament

In accordance with the given requirements, two M134 Miniguns provide the VVV's fire support. Remote operation of the miniguns would be possible with BAE systems Remote Guardian System (RGS), pictured in Figure 5. The RGS uses a continuously computed impact point allowing for point and shoot operation as the system constantly compensates for wind and vessel motion [6]. The system has infrared imaging through FLIR cameras, allowing for low visibility operation and improving night navigation capabilities. Placement of turrets near the bow and the stern would ensure 360 degree coverage at a

range of elevation angles. Remote operation removes the operator from the line of fire, placing them behind the ballistic protection of the pilothouse.

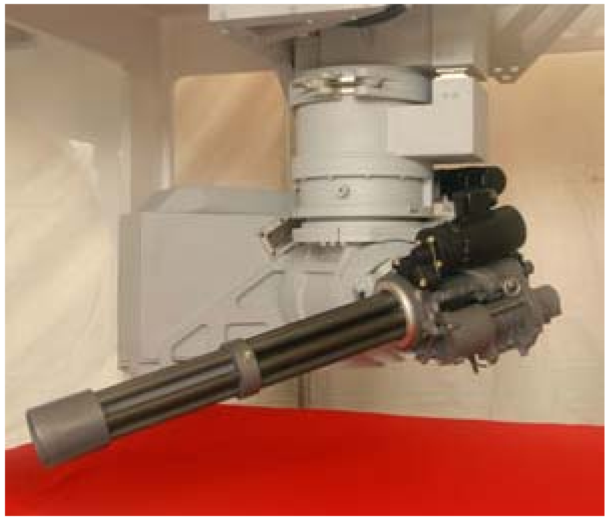

Figure 5: Minigun with Remote Guardian System

4. Hull Form

Selection Process

Multiple hull forms were considered for the VVV. The benefits and drawbacks of each choice were evaluated. The hull forms considered were:

- Planing Monohull
- Surface Effect Ship
- Air Lubricated Hull
- M-Hull
- Multihull (Catamarans and Trimarans)
- Monocat

These hull forms were placed into a concept screening matrix and qualitatively evaluated against 11 criteria to reduce the number of valid concepts. Crosswise pairing of criteria in an analytical hierarchy process produced weights for these factors. Finally, the hull forms were quantitatively evaluated in a concept scoring matrix. Appendix B thoroughly details the process arriving at the final design.

Careful consideration of the designs determined a planing monohull would be the most effective form for the VVV. Due to size restrictions, dynamic lift or resistance reduction was necessary to increase speed beyond the displacement range. A planing hull achieves

its increased speed by skimming across the surface of the water rather than plowing through the water, resulting in a reduction of wetted surface area and a corresponding decrease in resistance. Experience has also shown that planing hulls are highly maneuverable, ideal for patrol/interdiction vessels.

A monohull also provided the large, centralized interior volume needed for cargo and seating. The design afforded a reasonably sized space that was low enough in the vessel to preserve stability. Its high freeboard allowed the outfitting of armor to cover the personnel transport compartment.

Planing monohulls are a proven concept and would ease design, construction, and maintenance and thus reduce cost. The hull could be reinforced and made appropriately rugged for repeated beaching operations.

Hull Design

Due to difficulties obtaining an appropriate parent hull, the VVV hull was developed using Maxsurf, an integrated naval architecture & ship construction program. This tool enabled the design to be exported into other Maxsurf suite programs for hydrostatic, stability, and seakeeping analyses. The parameters for planing calculations were taken from this hull (see the Resistance, Powering, and Propulsion section).

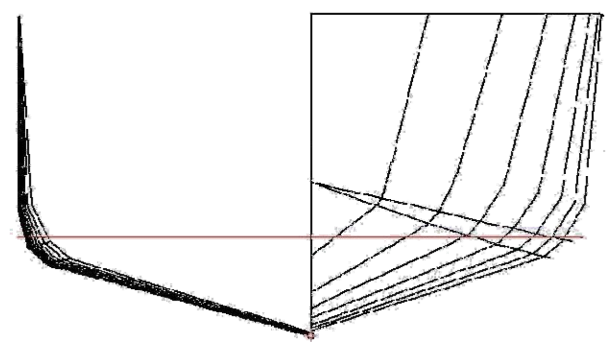

Figure 6: Hull Section View

The chosen hull maximized the vessel footprint within the davit restrictions. The difficulty of seating a standard Marine rifle platoon was a driving design factor. Midship beam was set at 4.5m and length overall was confined to 15m to allow aft-transom space for waterjets (see Resistance, Powering & Propulsion section). One benefit of this relatively wide beam was the maximized planing potential.

A traditional, chined planing hull was pursued from the outset. The double chine chosen was selected to reduce resistance over a single chine design. It should also reduce slamming loads and accelerations by offering a narrower waterplane area following flow separation. Strakes would have to be carefully designed to prevent ventilation by reducing air intake into waterjets.

After research into deadrise angle theory and precedents, a 15 degree deadrise angle was selected. Constant deadrise aft would provide a large, flat planing pad with a steeper V-

bow forward for finer wave entry. The chosen deadrise angle also provided a reasonable compromise between the seakeeping characteristics of a deep V and planing performance of a flat bottom boat. This was later found to be the lower limit of deadrise angles necessary to ensure tracking with waterjets [7].

The wall-sided hull design utilizes space efficiently while staying within davit restrictions. The vessel's high freeboard was designed for head-to-toe outfit of composite armor for the seating compartment. The sides should also limit wave splash on the deck. The freeboard should contribute reserve buoyancy, increasing large-angle and loaded stability. The reduced freeboard aft was designed to eliminate structure and weight aft to aid even-keeled trim in the unloaded condition.

5. Weights

Weights were estimated using data gathered from similar craft, scholarly projects, and manufacturers and summarized in the Ships Work Breakdown Structure (SWBS). Table 2 summarizes the main SWBS groups compromising the lightship weight and the deadweight loads. Estimating procedures for each group are detailed in the following sections.

Weight Group	Weight (tonnes)
100 Structures	5.4
200 Propulsion	4.8
300 Electric Plant	1.1
400 Command and Control	0.5
500 Auxiliary Systems	1.9
600 Outfit and Furnishings	3.1
700 Armament	0.3
Total Lightship	16.0
Total Lightship w/ 5.9% Design Margin	**16.9**
Diesel Fuel (300 nm range)	2.3
Marine Platoon w/ Gear (fully loaded)	5.0
Miscellaneous (crew, stores, etc.)	0.5
Deadweight Loads	**7.8**
Full Load Displacement	**24.7**

Table 2: Ship Design Weight Summary

The SWBS 100 group for hull structure weight was estimated from ASSET/Hydrofoil[8] data. This source provides information on aluminum hydrofoil vessels without the added weight of foil structures. The composite armor around the pilothouse and platoon transport section was then added to the predicted weight. The hull structure weight scaled from the Combatant Craft-Riverine[4] (CCR) project confirmed this estimate, providing nearly the same weight.

Propulsion weight (SWBS 200) was estimated by scaling from the CCR project with respect to BHP and confirmed with vendor weight data. Propulsion data was continuously refined throughout the design process; final values for SWBS 200 were the result of multiple iterations. More information on propulsion calculations can be found in the Resistance, Powering and Propulsion section.

While the SWBS 500 weight estimate for Auxiliary Systems was also scaled, SWBS 300 (Electrical Plant), 400 (Command and Control), and 600 (Outfit and Furnishings) group weights were taken directly from CCR project data; these groups were considered to be very comparable. SWBS 700 (Armament) weights was calculated from contractor data for the BAE Remote Guardian System [6].

To account for uncertainty in the design estimate, a 5.9% design weight margin was added to the total lightship weight calculation according as recommended by the NAVSEA [9]. These weight estimates provided the lightship weight of the vessel.

Deadweight load calculations included all transient loads such as the USMC light infantry platoon of 43 Marines with gear. The 95th percentile height was assumed for the average height of ground troops. The average weight for that height was derived from MIL-STD-1472D [3]and used for the weight of each Marine. The term “Marine with gear” in this report refers to a light infantry Marine carrying a typical fighting and existence load for temperate zones. The total weight of a Marine with gear was taken as 265lbs, with a 175lb soldier carrying a 90lb pack.

Fuel for the high speed diesels was assumed to be Marine Gas Oil with a density of 7.5lbs per gallon. Fuel consumption data from the CAT 12 high speed diesel engine [10] was used to determine the required amount of fuel for the 300nm range. A 10% margin was used as well. The final amount of Marine Gas Oil was determined to be 695 gallons or 2.36 tonnes.

The relative size of the weight groups is shown in Figure 7.

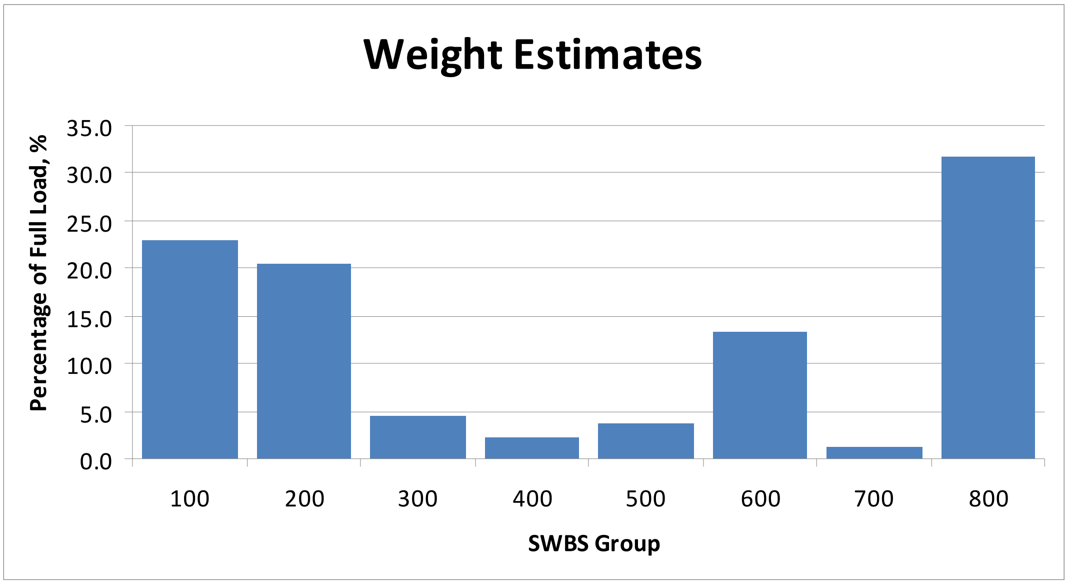

Figure 7: Ship Design Weight Breakdown

6. Resistance, Powering, and Propulsion

Savitsky's Method

Since model testing data or other reliable performance data was unavailable for the proposed design, estimates were produced using a planing boat performance prediction program provided by Professor Raju Datla of Stevens Institute of Technology [11]. A visual example of the software interface can be found in Appendix C. This program uses a method developed by Professor Daniel Savitsky, one of the foremost experts on planing craft, to predict resistance of small planing vessels with characteristics similar to the VVV. His method depends on several fundamental metrics used to describe the hull geometry and loading of planing monohulls [12].

Information required by Savitsky's method include:

- Displacement (Δ)
- LCG & VCG location
- Deadrise angle (β)
- Beam (B)
- Vessel speed (V)
- Propeller shaft-line inclination (ϵ)
- Propeller shaft-line distance from CG (f)

Information predicted by the method include:

- Running trim (τ)
- Wetted keel length (L_k)
- Wetted chine length (L_c)
- Total resistance (D)
- Draft at keel (h)
- Required propulsor thrust (T)

The Savitsky method uses an iterative technique to satisfy the equilibrium of moments about the CG shown in Figure 8. The thrust line from the propulsor was assumed to act through the CG for the preliminary calculation.

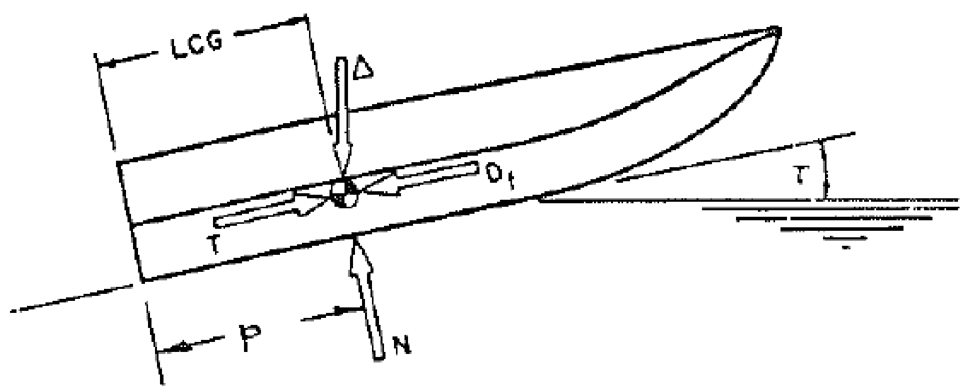

Figure 8: Idealized Situation with Concurrent Forces Acting at CG [13]

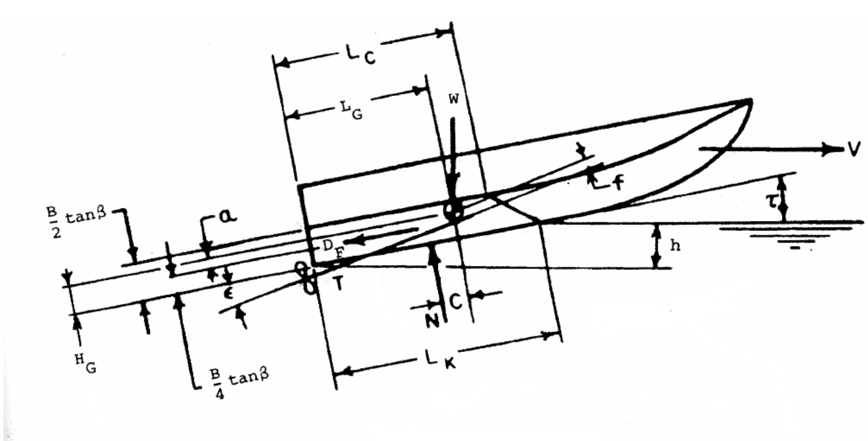

Figure 9: General Case of Non-Concurrent Forces on a Planing Craft [13]

The results of these calculations are summarized in the graphs in Appendix C.

Resistance

Figure 10 shows effective power (EHP) versus vessel speed for a variety of LCG locations. Appendix C contains graphs showing running trim versus vessel speed. The VVV's cruise speeds fall in the post "hump" region of resistance data. This range of vessel speeds is often associated with a craft in the planing regime. The results provided by this information were assessed to make preliminary decisions on target LCG locations under loaded and unloaded conditions. A loaded LCG of 21 ft (forward of transom) gave least resistance at cruise speed. An LCG of 17.8 ft gave least resistance at cruise speed during the unloaded condition. General arrangements of the VVV were made to accommodate these results.

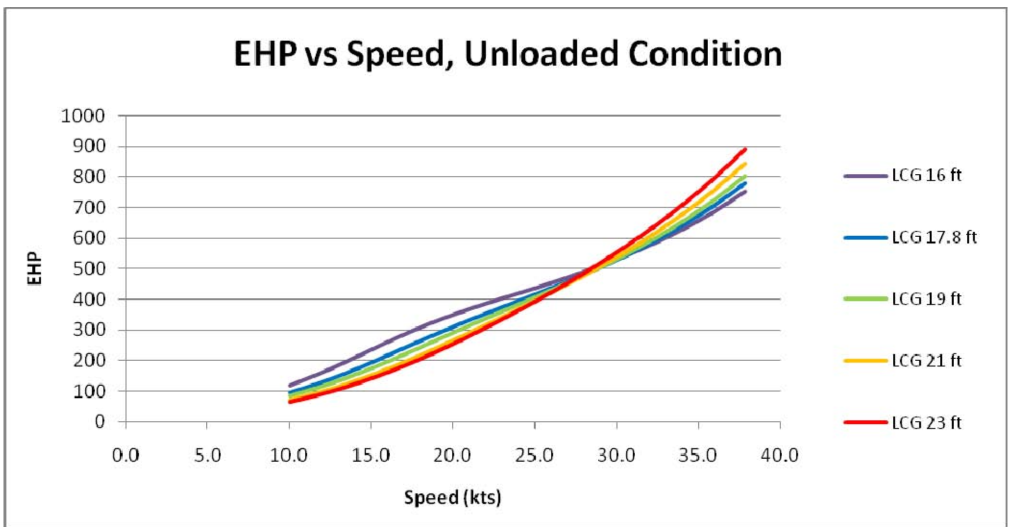

Figure 10: EHP vs. Speed, Loaded Condition

The program estimated an effective horsepower (EHP) of 669 hp based on the power needed to propel the VVV at 35 knots unloaded in calm water. The powering and propulsion analysis continued with the selection of a propulsor type to determine the installed horsepower after applying appropriate margins.

Powering

Waterjets, as well as conventional, surface-piercing, and ducted propellers were considered. Propellers were found to be more efficient in the vessel's cruise range, though upsizing the waterjet impeller and housing diameters would improve both thrust

and propulsive coefficient (PC) particularly at lower speeds [14]. Ultimately, there were functional issues that led to selection of waterjet propulsion.

Waterjet propulsion nearly eliminates appendage drag, maintaining the shallow draft necessary for operation in riverine and beach environments. Waterjets, unlike propellers, operate efficiently independent of boat speed[14]. This means full power can be applied when the vessel is at rest. This feature is important for self-extraction from a beached condition. Additionally, this propulsion system can be soft-mounted to the hull, resulting in a quieter drive that doesn't propagate structure-borne noise [15]. Waterjets typically fare better when the vessel is overloaded or running light, a serious concern in a vessel where deadweight loads account for 32% of all-up weight.

Waterjet Propulsive Coefficient (PC) data indicated PCs of 0.46 - 0.63 in the VVV's speed range, with the higher values corresponding to increasing speed [14]. This PC data was applied to the estimated effective power to obtain ideal brake horsepower (BHP) vs. speed curves for both the loaded and unloaded conditions.

ITTC recommended values for powering margins were used to allow for the operation of the VVV in realistic conditions. Where the proceedings recommended a range, the middle of the range [16] was selected. The resulting margins are tabulated in Table 3.

	% MCR		
Margin	**Low**	**High**	**Chosen**
Sea	15	25	20
Engine Operation	10	15	12.5
Light Running	5	7	6

Table 3: Powering Margins

Sea margin allots a power reserve to compensate for increased resistance due to weather and sea forces, hull fouling and roughening, and wear on impeller blades. The engine operation margin allows for economical operation at design speeds to minimize fuel consumption and maintenance intervals. The light running margin accounts for "the margin in impeller speed considered necessary for a ship to continue to absorb 100% engine power."[16]

The resulting BHP vs. speed graph shown in Figure 12 considers the engine operation and light running margins for each case. The sea margin was independently applied to

generate a rough water curve corresponding to each calm water curve. The area between the calm water and sea margin curves reflects the range of possible speeds in changing sea conditions for either the loaded or unloaded case.

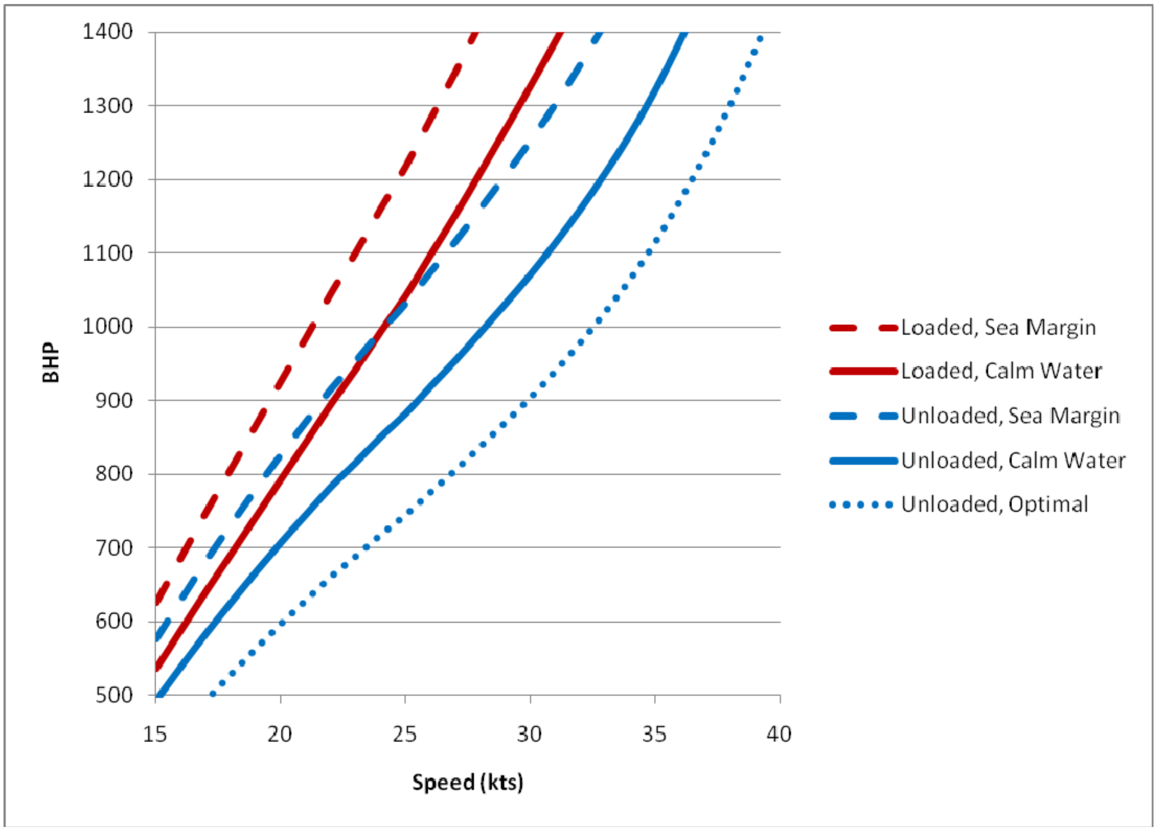

Figure 11: Power vs. Speed Curves

The 35 knot unloaded target speed was the more stringent requirement. The ITTC light running and engine operation margins were applied to ensure the boat could meet this maximum design speed in trials and continue to achieve a calm water speed of 35 knots across the life of the boat. The sea margin was not included in determination of necessary maximum BHP because the 18.5% engine operation plus light running margin was judged to be sufficient to ensure dictated performance. Given optimal mechanical and thermodynamic efficiency, the vessel is estimated to reach 38 knots unloaded in builders' trials (see the "unloaded, optimal" curve in Figure 11). The unloaded, calm water curve (solid blue) dictates a total power of 1,320 BHP for the design sprint speed. This rating ensures that the vessel will also surpass required sprint speed for the loaded case in a variety of sea conditions.

Propulsion Machinery

High-speed diesels were selected as the prime movers. Twin diesels reduce the length of the engine/machinery room, allotting much-needed space to accommodate the sizeable crew transport compartment. They would also provide a measure of redundancy, allowing continued vessel operation in the event of a single engine or propulsor failure.

Powering calculations indicated the need for a marginal continuous rating (MCR) of 660 hp for each engine. Notable manufacturers with models in the 660 to 675 BHP range include Caterpillar, Volvo, MTU Detroit, Scania, and Cummins. Caterpillar CAT C12 660 hp engines were selected for preliminary calculations due to their relatively compact size and high power-to-weight ratio[10].

An examination of the BHP vs. speed curves showed that the power required to achieve the 18 knot cruise speed was less than 62% of MCR. To avoid engine underloading and associated problems such as overcooling, the vessel's cruise speed was increased since this would also increase the efficiency of the waterjets. Given that the CAT C12 had a nearly flat specific fuel consumption (SFC) curve[10], the 75% MCR rule was selected as the lowest point for continuous safe operation[17]. The resulting sprint and cruise speeds are summarized below and expressed as a range to reflect the change in speed from calm to rough water equivalent to the sea margin.

	Speed (knots)	
Condition	**Cruise**	**Sprint**
Loaded	21-24	27-30
Unloaded	24-28	31-35

Table 4: Cruise and Sprint Speeds

7. General Arrangements

Locations of equipment and spaces in the vessel were selected to optimize centers of gravity, ergonomics, and space efficiency. The vessel was divided into six sections that included space for the engine room, accommodations, pilothouse, transport area, outfitting/tankage, and bow/ramp systems.

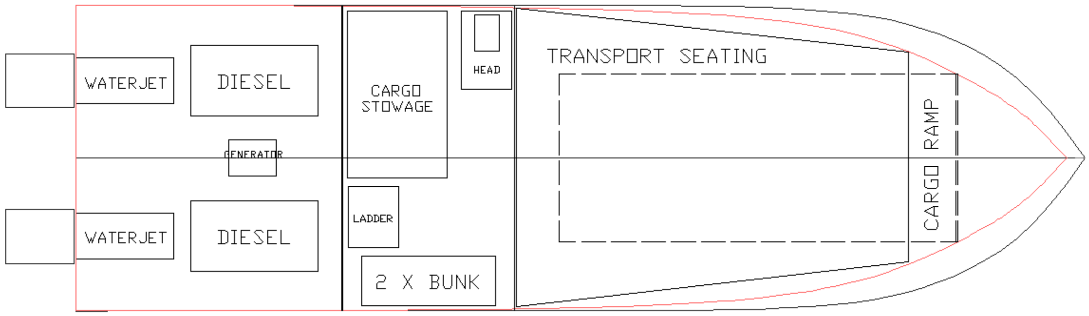

Figure 12: Plan View

The location of the cargo area was a primary concern since troops and cargo comprise 21% of the VVV's total displacement in the loaded condition. Optimal LCG was achieved for both conditions by offsetting the large aft loading of the machinery spaces with the placement of the cargo area.

After completing powering calculations, preliminary selections were made for engine and propulsor models: dual Caterpillar CAT C12 diesels [10] and HamiltonJet HJ403 waterjets[18]. These dimensions provided an estimate for required sizing of the aft machinery spaces.

The hull inner bottom beneath the cargo deck was assigned to support systems including operation of the cargo loading and offloading systems in the bow, storage, ballast tanks, electrical, HVAC, and plumbing.

An open bow door concept was designed to reduce collection of water wash into the transport seating deck. This deck was raised six inches above the loaded waterline for this reason. The weather deck included a slight camber and the deck was sloped toward the bow to promote drainage.

A traditional drop-down bow ramp design was not used to reduce resistance and minimize slamming loads in higher sea states. The bow and ramp system selected was arranged for safety, simplicity and dependability. The entire bow section swings to starboard to reduce the number of moving parts and eliminate possible leakage through a centerline seal. The hinged, one-piece gate included the collision bulkhead to maintain the structural integrity of the bow. The cargo ramp was designed to accommodate typical structures present in the inner hull bottom, including transverse and longitudinal elements. It also supports operation of the hover pallet by providing an appropriate surface for aircushion systems.

The pilothouse was placed to afford the crew acceptable visibility. Interior space was allocated with consideration to navigation and communication equipment and remote operation of defensive systems. The bridge provides suspension seating for three crew members and the platoon commander.

The VVV incorporates two exit routes from each inboard space. A ladder gives access to the pilothouse from the accommodations space. A 5 x 5 ft hatch located on the ceiling of the cargo area can be opened from the inside and used as a second exit path or for loading of cargo pallets. The accommodation space is designed for three days of operation and includes a head, two bunks, seven cubic meters of storage area, and an access point to the cargo area.

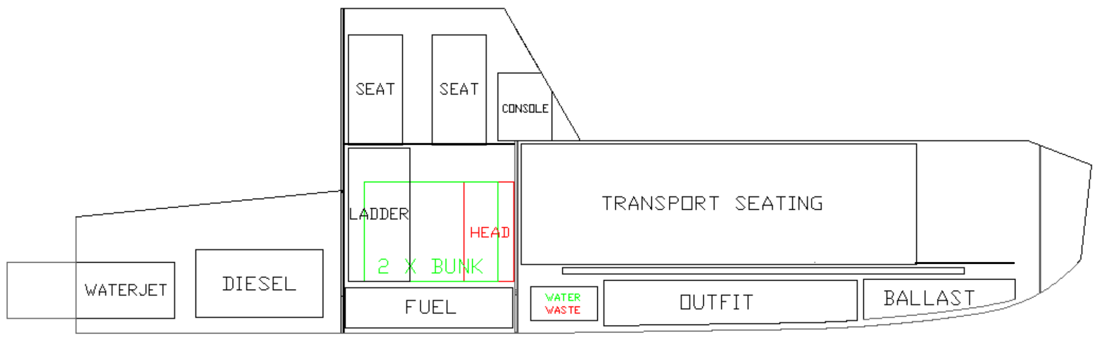

Figure 13: Inboard View

Bulkheads were located to meet American Bureau of Shipping (ABS) rules for High Speed Naval Craft (HSNC) of at least 15m. A collision bulkhead was added 5% of the total length aft of the stem and a watertight bulkhead encloses the engine room. An additional bulkhead separates the cargo and accommodation spaces.

8. Principal Characteristics

Table 5 summarizes the principal characteristics of the Very Versatile Vessel.

Displacement, Loaded	24.7 tonnes
Displacement, Lightship	16.9 tonnes
Length (Overall)	16 m
Beam	4.5 m
Draft	0.838 m
Installed Power	1,350 hp
Speed, Sprint (Unloaded)	35 kts
Speed, Cruise	24 kts
Range	300 nm
Crew	3
Military Lift	43 Marines or 3 tonnes cargo
Hull Material	5086 Al

Table 5: Principal Characteristics

9. Stability and Seakeeping

Stability

A stability analysis of the VVV was performed with the aid of the ship design tool Hydromax. The righting arm curve in Figure 13 provides information about large-angle roll stability. The maximum righting arm occurred at approximately 40 degrees, with an angle of vanishing stability of 82 degrees.

Additional information about stability can be gleaned from the hydrostatic characteristics in Appendix E. The transverse metacentric height (GM_t) of the VVV was obtained from this table and determined to be 2.1m loaded and 2.4m unloaded. This GM_t value was equal to between 47% and 53% of the beam and deemed reasonable for a planing boat of the VVV's geometry. This result is typically associated with excellent stability and was expected due to the large beam and shallow draft of the VVV.

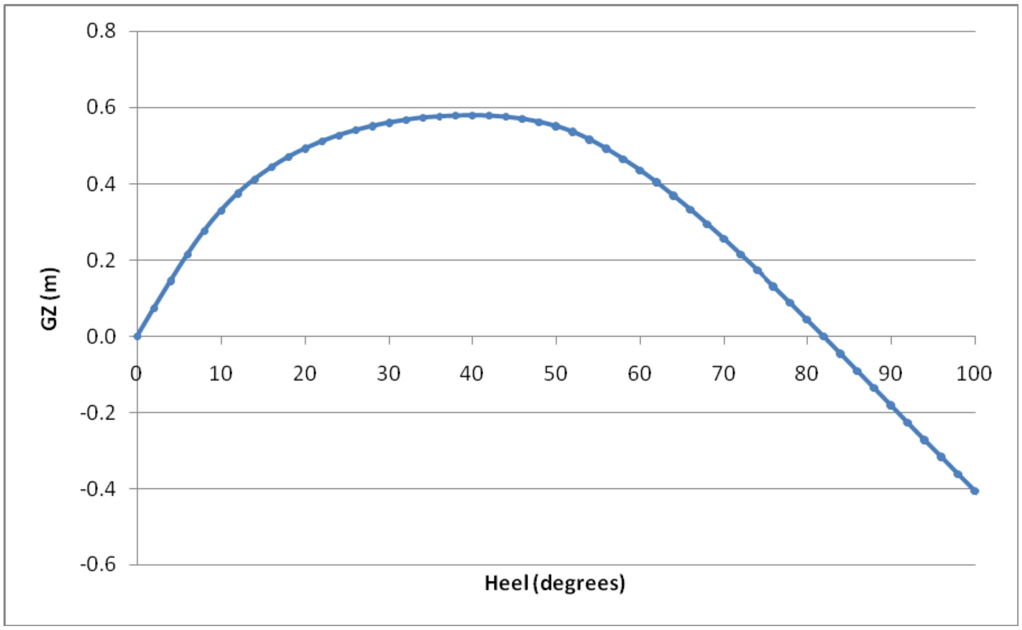

Figure 14: Righting Arm (Loaded Condition)

Seakeeping

Seakeeper, another Maxsurf suite program, was used for a seakeeping analysis of the craft. Since the software analysis is only valid for displacement hulls, VVV seakeeping could not be evaluated in the planning mode. However, VVV's motions were evaluated in displacement mode at a speed of 10 knots. The vessel was subjected to ITTC wave spectra for Sea States 4 and 5 to determine operational and survivable limits. Headings from 0 degrees (following seas) through 180 degrees (head seas) at 45 degree intervals were evaluated to generate radar plots for key parameters. Graphs of Motion Induced Interruptions and Motion Sickness Index versus heading are shown in Figures 15 and 16, respectively. These polar plots illustrate the effects of sea state and heading on the troops and crew. Further polar plots of boat motions (heave, pitch, and roll) by sea state and vessel heading are included in Appendix G.

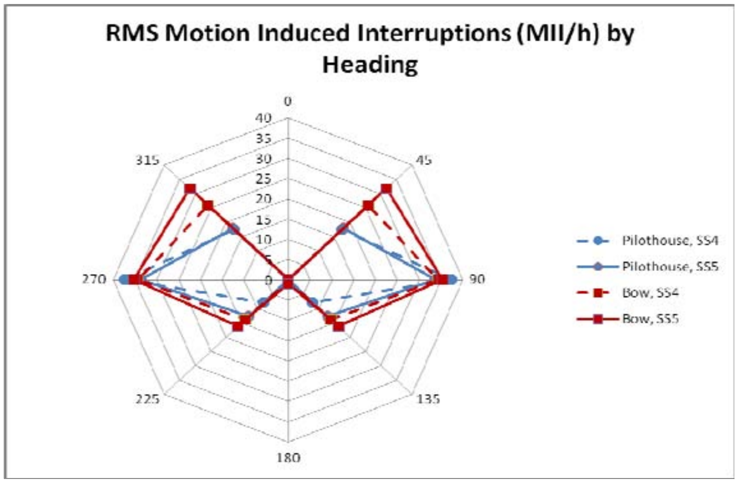

Figure 15: RMS Motion Induced Interruptions by Heading

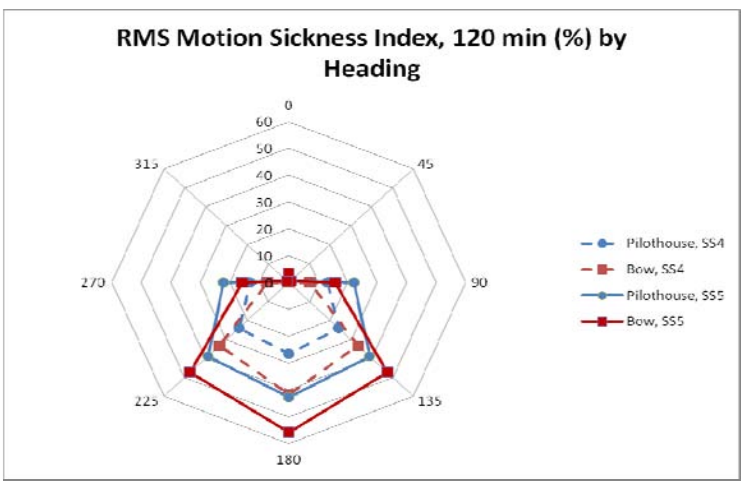

Figure 16: RMS Motion Sickness Index by Heading (120 Minute Exposure)

Habitability

Of the many factors that contribute to performance, one of the most important in the minds of the crew is ride quality. Crews and troops aboard high-speed military craft incur increased physical stress and injuries as a result of various motions. One of the most significant of these motions is vertical impact accelerations. These accelerations are incurred when the planing hull plunges into waves. The jarring impact caused by these accelerations results in various injuries and severely impacts the ability of the crew or troops to conduct their assigned missions. Accordingly, it is important to understand how the VVV handles various sea states and what impact accelerations would result.

The methods used to predict these impact accelerations are detailed in Appendix G. The techniques yielded a maximum vertical acceleration of 8.7g at the bow when traveling at sprint speed in Sea State 4. It should be noted that this figure assumes traveling at sprint speed in maximum sea state and is calculated at the bow (farther forward than any of the seats). A more relevant figure would be the 4.6g force at the bow when fully loaded at cruise speed in Sea State 3 where most littoral operations would be conducted. When conducting riverine operations, wave height and therefore impact accelerations should be significantly less

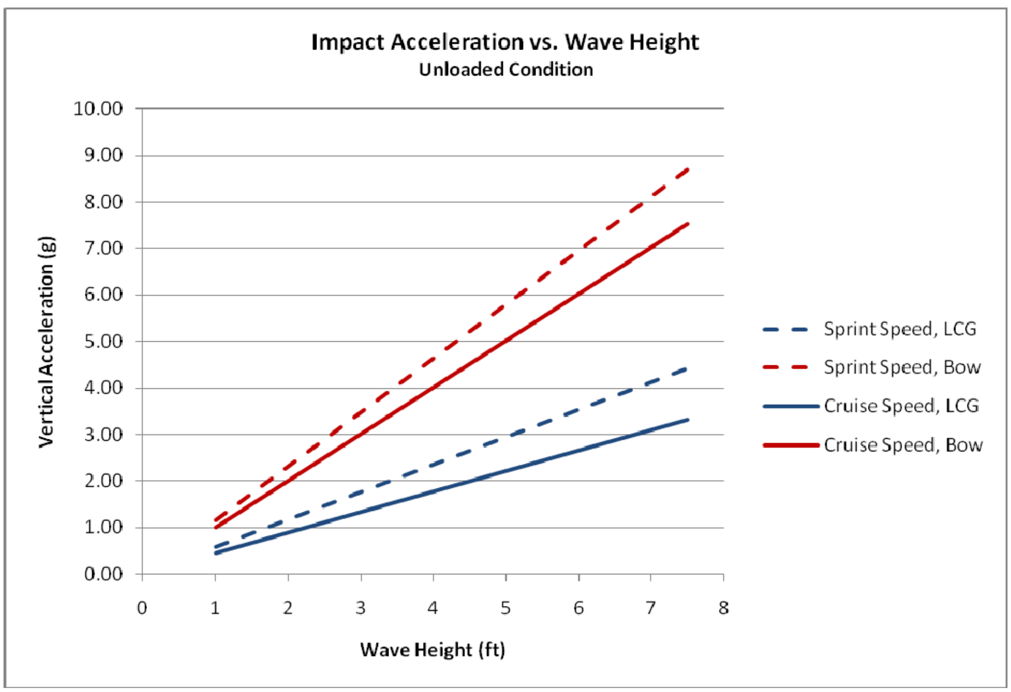

Figure 17: Impact Accelerations vs. Wave Height (Unloaded)

10. Conclusions

The preliminary design of the Very Versatile Vessel presents an innovative solution for expanding amphibious capabilities of the current United States Navy. Amphibious forces presently lack a vessel that can provide the ability for quick launch and recovery along with a significant personnel and cargo lift capability. Research was compiled in different areas including lightweight materials, arrangement of spaces, shipboard systems and application of calculated data. The design presented in this report integrates elements of both patrol and landing craft into a versatile, mult-imission vessel. Suggestions that may aid further research on a vessel of this nature are provided.

Further research on the following topics for the Very Versatile Vessel is recommended:

- A modular mid-body section that would expand operational capabilities to a variety of roles not included in the design requirements
- An expandable design that would allow the VVV to expand transversely beyond beam limitations of the davit
- Bow gate/ramp investigation and refinement
- Further development of the hoverpallet concept
- Seakeeping analysis in planning mode
- Structural analysis
- Continued weights iteration
- Analysis of damage stability

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Appendices

Appendix A: Statement of Requirements

I. Introduction

A. Additionally, Landing Platform Docks have operated with displacement and air cushion based landing craft providing personnel, vehicle and cargo lift to the beach. The designs of such vessels are heavily compromised by the need to provide a beaching capability and the ability to fit within a well dock or operate from davits.
B. It is proposed to replace the smaller personnel landing craft with a "Very Versatile Vessel" capable of transporting personnel and light cargo but with a superior capability to undertake patrol and interdiction missions in Littoral and Riverine areas.
C. The vessel's weight and dimensions are to remain compatible with davit operations from an amphibious assault ship in a seaway.

II. Aim

A. To design a Very Versatile Vessel to provide the capability to support amphibious and Riverine operations circa 2015. To identify technical issues and requirements associated with that design that require further investigation and development.

III. Ship Design Requirements

A. The vessel shall be capable of undertaking the following missions:-
   1. Riverine and littoral patrol.
   2. Littoral interception of hostile vessels.
   3. Personnel and cargo delivery from LPD to shore through the surf zone.
   4. Insertion of Light Infantry forces.
B. The ship design shall meet the specific requirements detailed at Appendix A

IV. Areas Of Technology Exploration

A. The use of alternate hullforms and / or dynamic assistance, such as Surface Effect Ships or multi hulls, to improve high speed performance and seakeeping within the limited weight, space, and draft footprints.
B. Use of advanced materials to reduce hull weight.
C. The integration of high performance propulsion units.

V. Constraints

A. The report and design shall be unclassified and all supporting information amended if necessary to allow this to occur.
B. The VVV shall remain operable from a davit of 26 tonnes and space of 16m x 4.5m. The vessel shall be able to operate from within the well deck of any US well deck ship.

VI. Approach

A. The team will review requirements and then brainstorm potential ideas.
B. Suitable ideas shall be assessed for architectural and ship interface impact and technical feasibility.
C. The competing ideas shall be reduced to a preferred concept using a decision making process.
D. A ship design synthesis model shall be developed.
E. A complete ship synthesis shall be undertaken. A balanced ship design shall result with performance analysis and a general arrangement developed.
F. The implications of any new technology or operational issues shall be noted. Recommendations for follow on work shall be developed.

VII. Deliverables

A. All work will be documented in a CISD Project Technical Report. The final report and presentation shall be suitable for unclassified, public release.
B. During the first 2 weeks the team will produce a team project plan of actions, assignments and milestones to be presented to CISD leadership form approval. During the project this plan shall be maintained.
C. The team will develop and give informal intermediate presentations and a final project presentation.

D. The resulting ship design shall be detailed including a single sheet summary of characteristics including estimated performance, a comprehensive SWBS breakdown, a hullform body plan and a full general arrangement drawing.
E. The team will be encouraged to produce a technical paper from the final report that would be published at a professional society conference in the future.

Functional Area	Requirement	Target
INTEROPERABILITY		
Davits	The User shall be able to operate VVV from current davits.	Dimensions within 16 m x 4.5 m. Overall weight limit of 26 te.
Dock	The User shall be able to embark payloads from the dock of an LPD 17 with the well deck flooded.	Operate from LPD-17 dock.
PERFORMANCE		
Speed	The User must be able to operate VVV at specified speeds.	35 kts Unladen, 25 kts laden
Force Projection	The User must be able to employ VVV to deliver 1 USMC light platoon with full combat equipment.	1 Platoon in each VVV
Sea State (Operations)	The User must be able to operate VVV in open oceans.	SS4
Sea State (Survival)	The User shall be able to reach safe haven.	SS5
Range	The User must be able employ VVV at the specified range.	300 nm
Endurance	The User must be able to operate VVV for x hrs and y speed to conduct a mission profile.	300 nm at Cruise Speed, 18 kts
Beaching	The User shall be able to operate VVV over a beach with the specified gradient.	1:120 beach
Embarked Personnel - load	The User must be able to embark troops.	1 Platoon in each VVV
Cargo Load	The VVV must be able to carry a specified cargo alternative to combat personnel.	2 tonnes
Dismount	The User must be able to disembark the troops (with full equipment) at the beach.	Requirement to dismount at beach. No speed target.
Seating - crew	The Operator shall be able to be seated under cover when underway.	Three seats in wheel-house

Seating - LF	The Landing Force shall be seated under cover when underway.	One seat per man
Firepower - protection	The vessel will be fitted with 2 x Mini Gun.	Fit 2 x Mini Gun
Firepower - protection	The User must be able to engage targets approaching from a 360^o arc, and at -10^o to 50^o elevation in self defence.	360 Arcs
ENVIRONMENT		
Riverine / Estuarine	The User must be able to operate VVV in riverine and estuarine environments.	
Surf	The User shall be able to operate VVV through surf.	1.75 m surf
FUNCTIONALITY		
Protection	The User must be able to employ VVV capable of withstanding small arms fire above the water line.	Maximize armor within weight limits.
Protection	The Crew shall be capable of creating a smoke screen.	360 degree coverage required.
Magnetic Signature	The Craft shall have as low a magnetic signature as possible.	Minimize signature.
Visual Signature	The VVV Craft shall have as low a visual silhouette as possible.	Minimize signature.
Towing	The User shall be able to employ VVV to tow another VVV.	Tow a second VVV at 5 knots in SS5.
INFORMATION		
Combat System	The User shall have access to a command and control system that allows shared situation awareness and communications between the LPD, the landing force and the VVV.	Fit Combat System to be agreed with customer.
Navigation	The User shall be able to operate VVV in navigational safety.	Fit Navigation System and standard navigation equipment.
PERSONNEL		
Crew	The User shall be able to operate the VVV craft and all weapon systems with the specified crew.	3 crew
LOGISTICS		
Duration - crew	The User shall be self-sufficient for the mission duration.	3 days
Life Saving Equipment	The User shall have access to life saving equipment.	Minimum Crew + Passengers +10%
Crew Stowage Facilities	The User shall be able to stow essential items safely and securely.	Stowage Space of 2 cubic meters
Regulations - LR	FLC Structure shall comply with appropriate regulations for Naval Shipping.	Comply with appropriate Class Rules

Appendix B: Hull Form Selection

Table 6: Concept Screening Matrix

Selection Criteria	Concept: Planing Monohull (Reference)	M-Hull	Air Cavity Craft	Planing Catamaran	Monocat	SES	Retractable Foiler	Expanding Trimaran
Vessel Size	0	0	0	0	0	0	0	0
Vessel Weight	0	0	0	-	0	-	-	-
Beaching/Unloading	0	+	0	-	0	+	-	0
Speed/Power	0	+	+	+	0	+	+	+
Interior Size	0	-	0	-	+	0	-	-
Durability	0	0	-	0	0	0	-	-
Stability	0	-	0	+	0	+	0	+
Seakeeping	0	-	0	0	0	0	+	+
Range/Endurance	0	+	+	+	0	+	+	+
Maneuverability	0	-	0	-	-	-	-	-
Maintenance	0	0	-	0	0	-	-	-
Signature	0	0	0	-	0	-	-	0
Sum +'s	0	3	2	2	1	4	3	4
Sum 0's	12	5	8	5	10	4	2	3
Sum -'s	0	4	2	5	1	4	6	5
Total Score	0	-1	0	-3	0	0	-3	-1
Rank	1	5	1	7	1	1	7	5

Table 7: Analytical Hierarchy Process - Crosswise Comparison

	Size	Weight	Beaching (Draft)	Speed/ Power	Interior Size	Durability	Stability	Seakeeping	Range	Maneuvering	Maintenance	Stealth	Total	%	Rank
Vessel Size	1	1/3	1/3	1/3	1/5	2	1/7	1/2	1/3	1/2	3	3	11.7	5.22	10
Vessel Weight	3	1	3	1/2	1/3	3	1/3	1/3	2	1/2	3	3	20.0	8.94	5
Beaching (Draft)	3	1/3	1	1/3	1/3	1/2	1/4	1	1/2	1	3	2	13.3	5.92	8
Speed/Power	3	2	3	1	1/3	2	3	2	1/2	3	4	3	26.8	12.0	3
Interior Size	5	3	3	3	1	2	1/3	3	1	3	2	3	29.3	13.1	2
Durability	1/2	1/3	2	1/2	1/2	1	1/3	2	2	1/2	3	1/2	13.2	5.88	9
Stability	7	3	4	1/3	3	3	1	4	5	4	3	5	42.3	18.9	1
Seakeeping	2	3	1	1/2	1/3	1/2	1/4	1	1/3	2	2	3	15.9	7.11	7
Range	3	1/2	2	2	1	1/2	1/5	3	1	1	3	3	20.2	9.03	4
Maneuverability	2	2	1	1/3	1/3	2	1/4	2	1	1	2	3	16.9	7.56	6
Maintenance	1/3	1/3	1/3	1/4	1/2	1/3	1/3	1/2	1/3	1/2	1	3	7.8	3.46	11
Stealth	1/3	1/3	1/2	1/3	1/3	2	1/5	1/3	1/3	1/3	1/3	1	6.4	2.85	12
													223.7		

Table 8: Concept Scoring Matrix

		Concept					
		Planing Monohull	M-Hull	Air Cavity Craft	Monocat	SES	Expanding Trimaran
Selection Criteria	Weight	Rating	Rating	Rating	Rating	Rating	Rating
Vessel Size	5.2	**3**	3	3	3	3	3
Vessel Weight	8.9	**3**	3	3	3	2	2
Beaching (Draft)	5.9	**3**	3	1	3	4	4
Speed/Power	12.0	2	3	**3**	2	5	4
Interior Size	13.1	5	**3**	4.5	3	3	2
Durability	5.9	**3**	3	2	3	2	2
Stability	18.9	**3**	3.5	3	3.5	2	4
Seakeeping	7.1	**3**	2	3	2	4	4
Range/Endurance	9.0	**3**	3.5	3.5	3	4	4
Manueverability	7.6	**3**	2	3	2	3	1
Maintenance	3.5	**3**	3	2	3	1	1
Signature	2.8	**3**	2	3	3	1	3
	Total Score	3.14	2.96	3.03	2.83	3.00	3.03
	Rank	4	5	3	6	2	1

Appendix C: Powering Methodology and Software

Davidson Laboratory "High Speed Planing Hull" User Interface:

Example Input Screens:

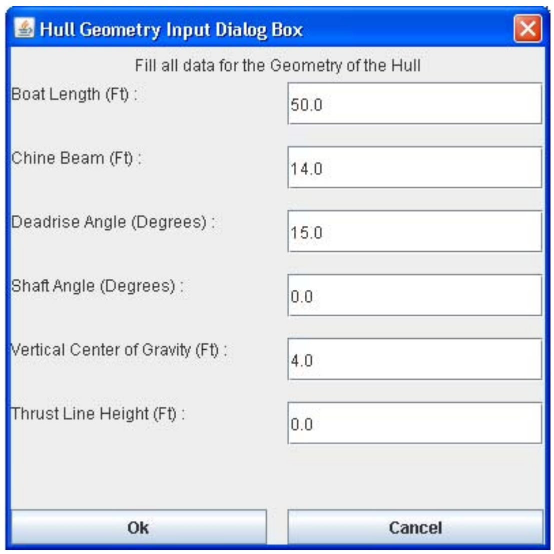


Figure 18: Hull Geometry Input

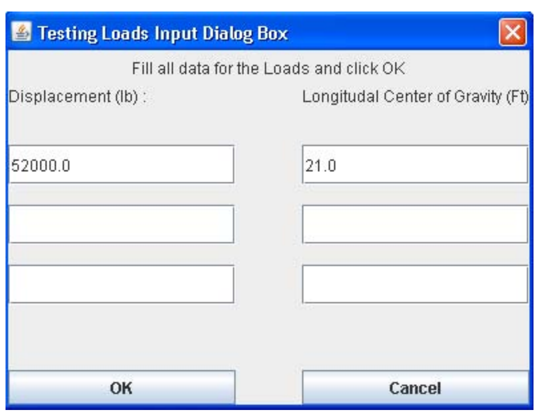


Figure 19: Input Displacement and LCG

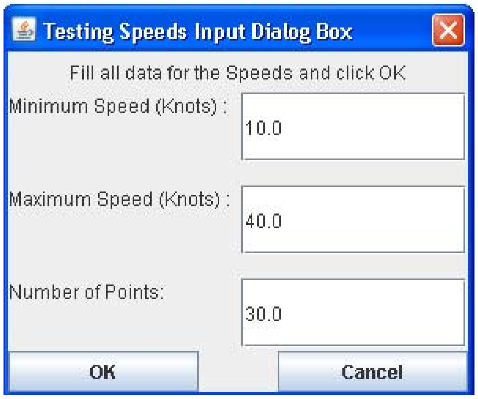
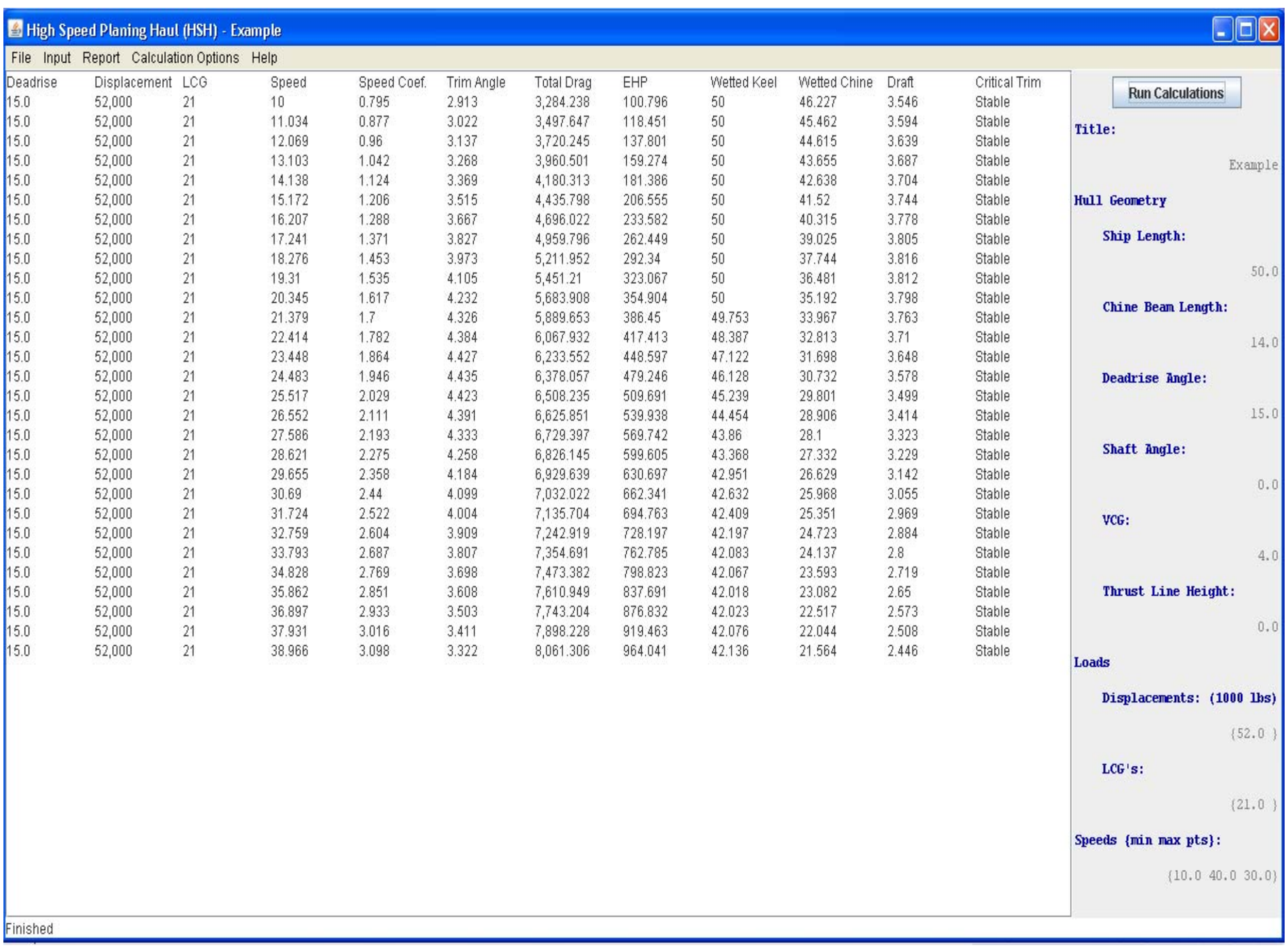


Figure 20: Speed Range Input

Sample Data Output Screen:



Deadrise	Displacement	LCG	Speed	Speed Coef.	Trim Angle	Total Drag	EHP	Wetted Keel	Wetted Chine	Draft	Critical Trim
15.0	52,000	21	10	0.795	2.913	3,284.238	100.796	50	46.227	3.546	Stable
15.0	52,000	21	11.034	0.877	3.022	3,497.647	118.451	50	45.462	3.594	Stable
15.0	52,000	21	12.069	0.96	3.137	3,720.245	137.801	50	44.615	3.639	Stable
15.0	52,000	21	13.103	1.042	3.268	3,960.501	159.274	50	43.655	3.687	Stable
15.0	52,000	21	14.138	1.124	3.369	4,180.313	181.386	50	42.638	3.704	Stable
15.0	52,000	21	15.172	1.206	3.515	4,435.798	206.555	50	41.52	3.744	Stable
15.0	52,000	21	16.207	1.288	3.667	4,696.022	233.582	50	40.315	3.778	Stable
15.0	52,000	21	17.241	1.371	3.827	4,959.796	262.449	50	39.025	3.805	Stable
15.0	52,000	21	18.276	1.453	3.973	5,211.952	292.34	50	37.744	3.816	Stable
15.0	52,000	21	19.31	1.535	4.105	5,451.21	323.067	50	36.481	3.812	Stable
15.0	52,000	21	20.345	1.617	4.232	5,683.908	354.904	50	35.192	3.798	Stable
15.0	52,000	21	21.379	1.7	4.326	5,889.653	386.45	49.753	33.967	3.763	Stable
15.0	52,000	21	22.414	1.782	4.384	6,067.932	417.413	48.387	32.813	3.71	Stable
15.0	52,000	21	23.448	1.864	4.427	6,233.552	448.597	47.122	31.698	3.648	Stable
15.0	52,000	21	24.483	1.946	4.435	6,378.057	479.246	46.128	30.732	3.578	Stable
15.0	52,000	21	25.517	2.029	4.423	6,508.235	509.691	45.239	29.801	3.499	Stable
15.0	52,000	21	26.552	2.111	4.391	6,625.851	539.938	44.454	28.906	3.414	Stable
15.0	52,000	21	27.586	2.193	4.333	6,729.397	569.742	43.86	28.1	3.323	Stable
15.0	52,000	21	28.621	2.275	4.258	6,826.145	599.605	43.368	27.332	3.229	Stable
15.0	52,000	21	29.655	2.358	4.184	6,929.639	630.697	42.951	26.629	3.142	Stable
15.0	52,000	21	30.69	2.44	4.099	7,032.022	662.341	42.632	25.968	3.055	Stable
15.0	52,000	21	31.724	2.522	4.004	7,135.704	694.763	42.409	25.351	2.969	Stable
15.0	52,000	21	32.759	2.604	3.909	7,242.919	728.197	42.197	24.723	2.884	Stable
15.0	52,000	21	33.793	2.687	3.807	7,354.691	762.785	42.083	24.137	2.8	Stable
15.0	52,000	21	34.828	2.769	3.698	7,473.382	798.823	42.067	23.593	2.719	Stable
15.0	52,000	21	35.862	2.851	3.608	7,610.949	837.691	42.018	23.082	2.65	Stable
15.0	52,000	21	36.897	2.933	3.503	7,743.204	876.832	42.023	22.517	2.573	Stable
15.0	52,000	21	37.931	3.016	3.411	7,898.228	919.463	42.076	22.044	2.508	Stable
15.0	52,000	21	38.966	3.098	3.322	8,061.306	964.041	42.136	21.564	2.446	Stable

Figure 21: Performance Prediction Output Data

Appendix D: Resistance Analysis

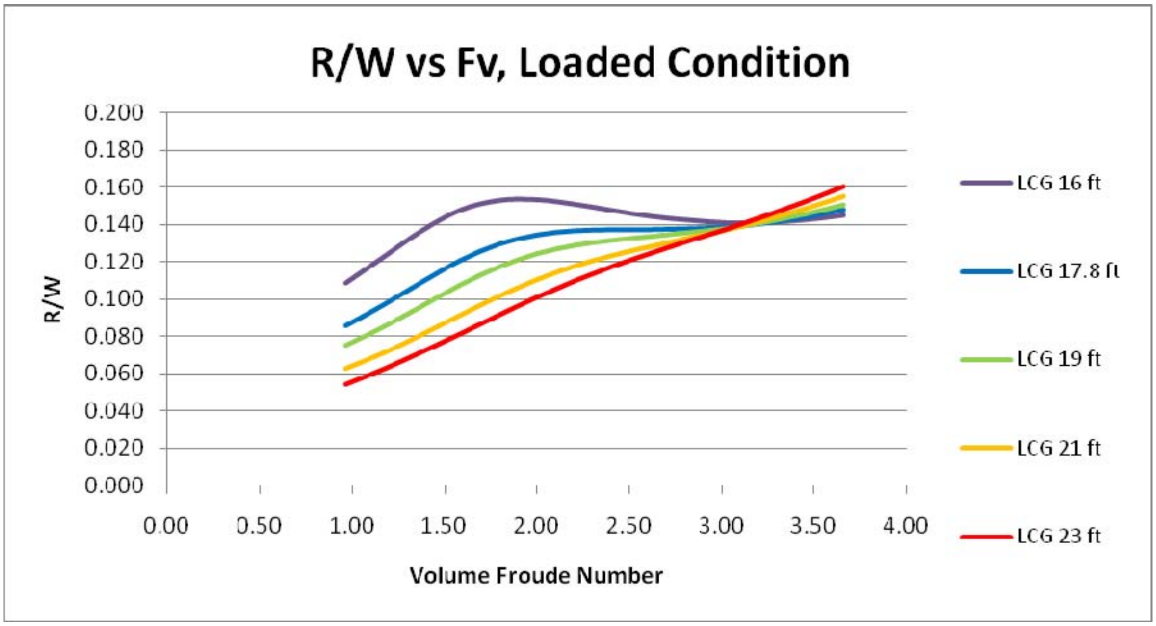


Figure 22: Resistance vs. Volume Froude Number, Loaded Condition

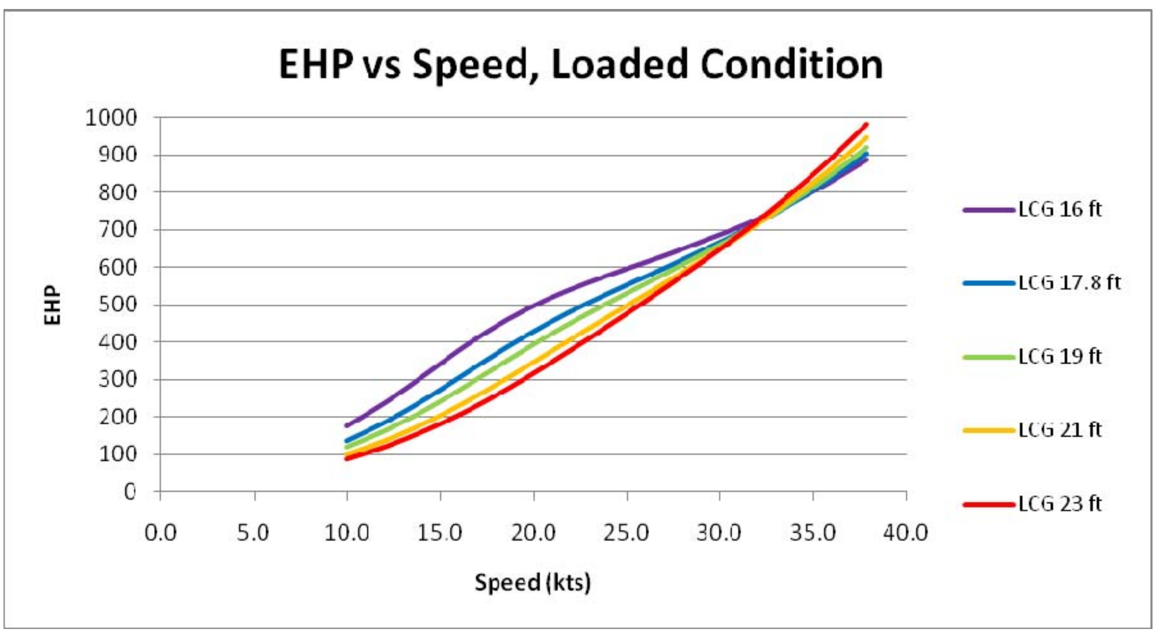


Figure 23: EHP vs. Speed, Loaded Condition

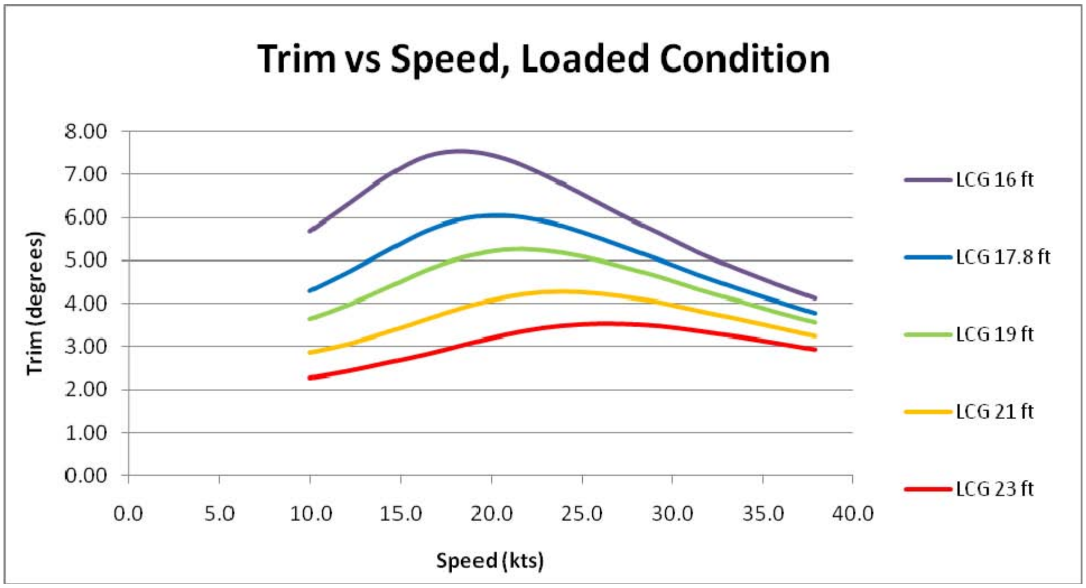


Figure 24: Trim vs. Speed, Loaded Condition

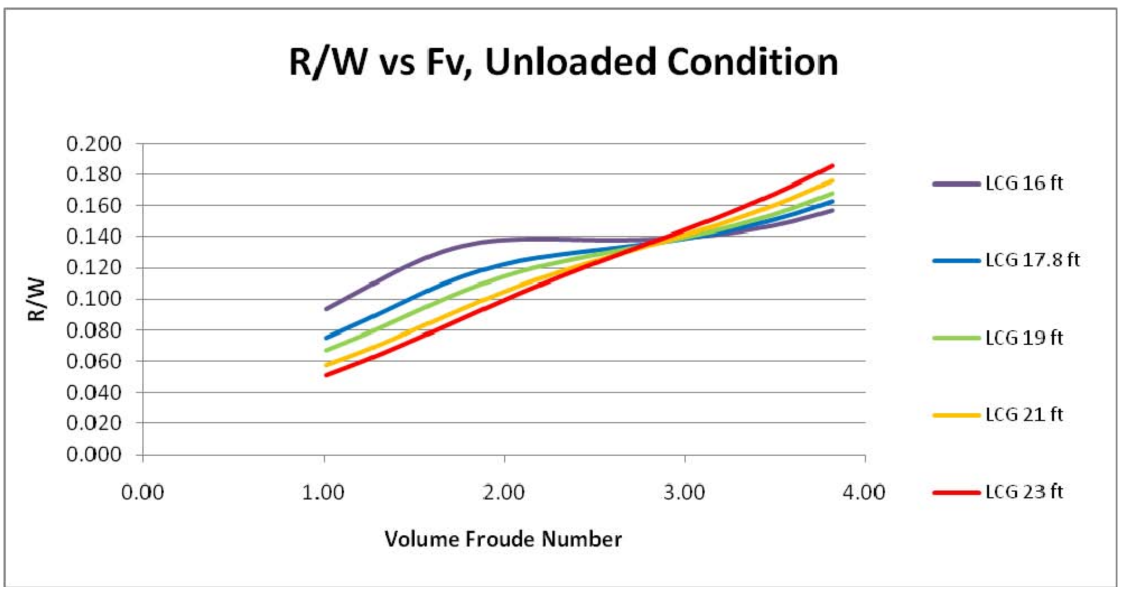


Figure 25: Resistance vs. Volume Froude Number, Unloaded Condition

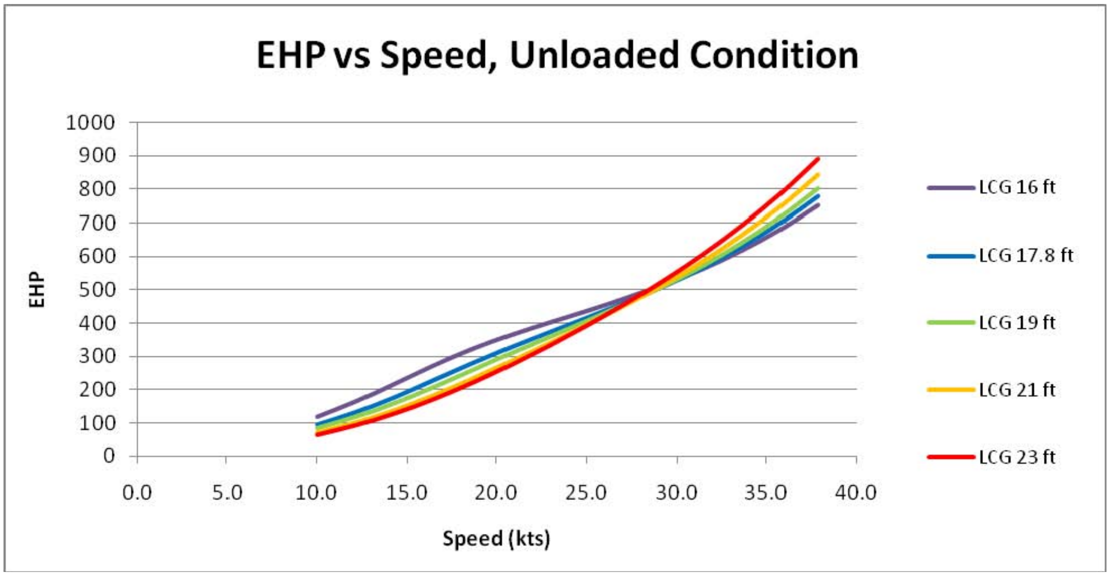


Figure 26: EHP vs. Speed, Unloaded Condition

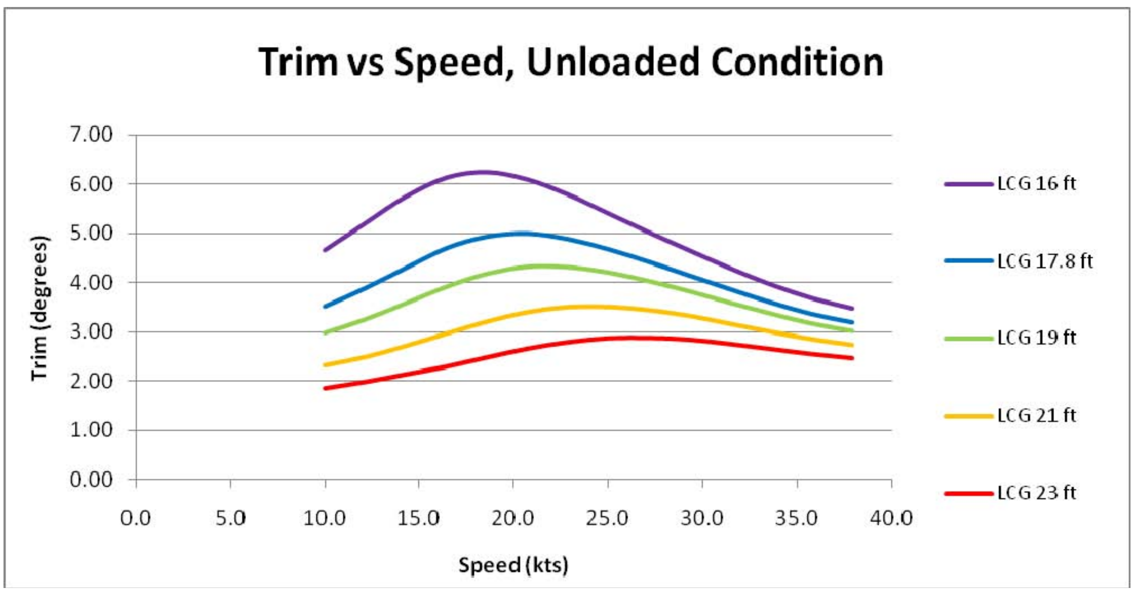


Figure 27: Trim vs. Speed, Unloaded Condition

Appendix E: Hydrostatics

Table 9: Equilibrium Hydrostatic Characteristics

	Condition	
Characteristic	**Unloaded**	**Loaded**
Draft Amidships (m)	0.68	0.79
Displacement (t)	19.34	24.43
Heel (deg)	0.00	0.00
Draft at FP (m)	0.46	0.75
Draft at AP (m)	0.90	0.84
Draft at LCF (m)	0.71	0.80
Trim (+ve by stern) (m)	0.44	0.09
Waterline Length (m)	14.14	14.62
Beam, Maximum Extents on WL (m)	4.51	4.49
Wetted Area (m^2)	53.99	59.82
Waterplane Area (m^2)	47.88	52.60
Prismatic Coefficient (C_p)	0.52	0.69
Block Coefficient (C_b)	0.34	0.44
Maximum Sectional Area Coefficient (C_m)	0.64	0.63
Waterplane Area Coefficient (C_{wp})	0.75	0.80
LCB from zero pt. (+ve fwd) (m)	5.36	6.25
LCF from zero pt. (+ve fwd) (m)	6.29	6.76
KB (m)	0.49	0.53
KG fluid (m)	1.55	1.59
BM_T (m)	3.49	3.17
BM_L (m)	29.20	28.86
GM_T corrected (m)	2.43	2.11
GM_L (m)	28.14	27.80
KM_T (m)	3.98	3.70
KM_L (m)	29.69	29.39
Immersion (TPC) (tonne/cm)	0.49	0.54
Moment to Trim 1cm (tonne-m)	0.37	0.46
Righting Moment at 1deg (tonne-m)	0.82	0.90
Maximum Deck Inclination (deg)	1.73	0.35
Trim Angle (+ve by stern) (deg)	1.73	0.35

Appendix F: Static Loading

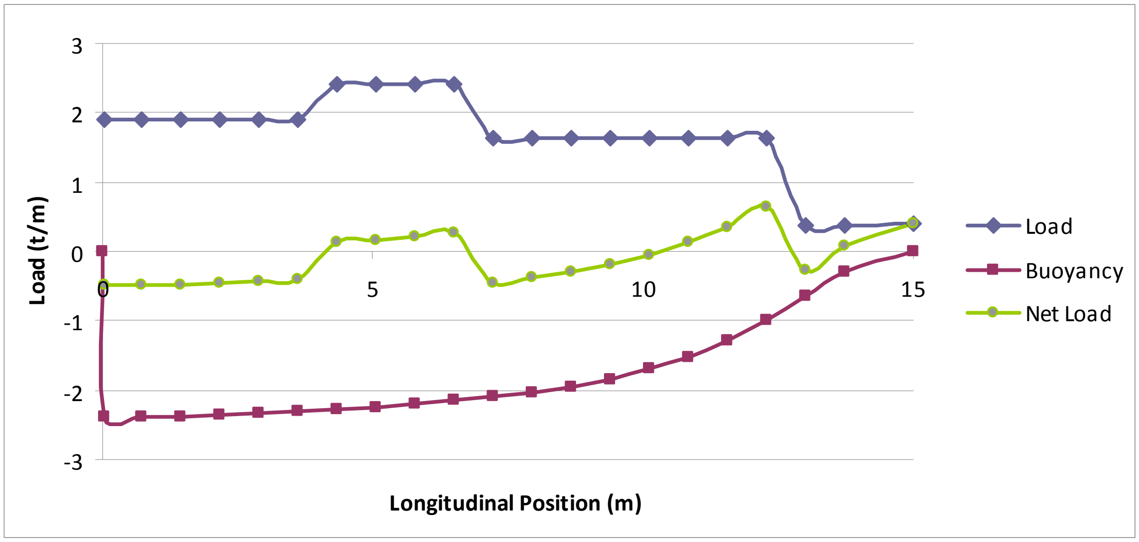


Figure 28: Vessel Loading, Loaded Condition

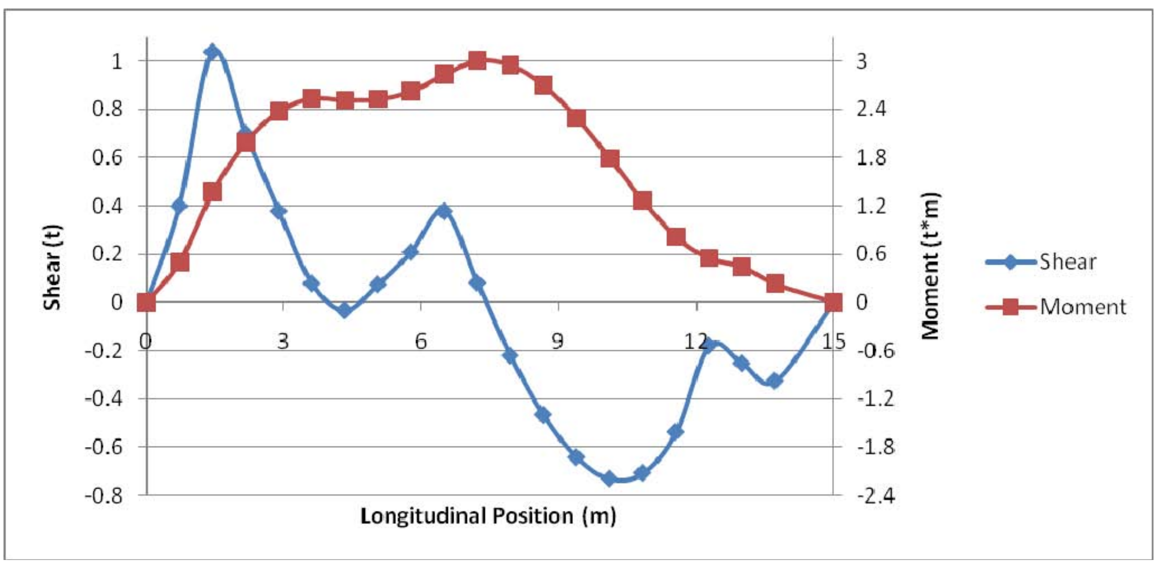


Figure 29: Shear and Moment Diagram, Loaded Condition

Appendix G: Seakeeping Assessment

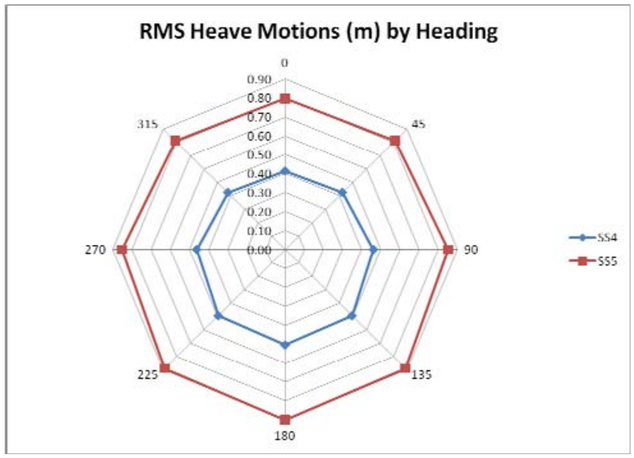


Figure 30: RMS Heave Motions by Heading

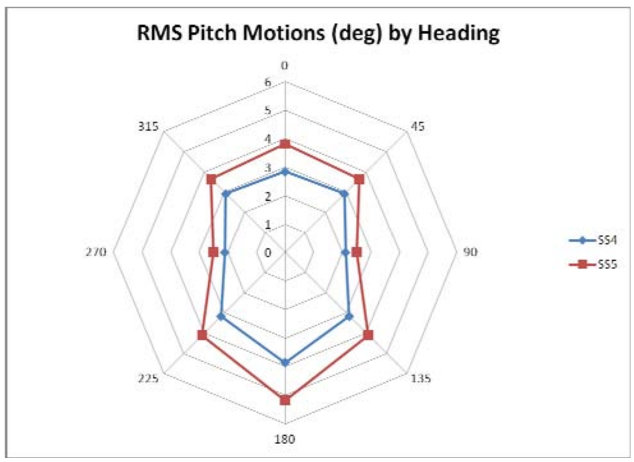


Figure 31: RMS Pitch Motions by Heading

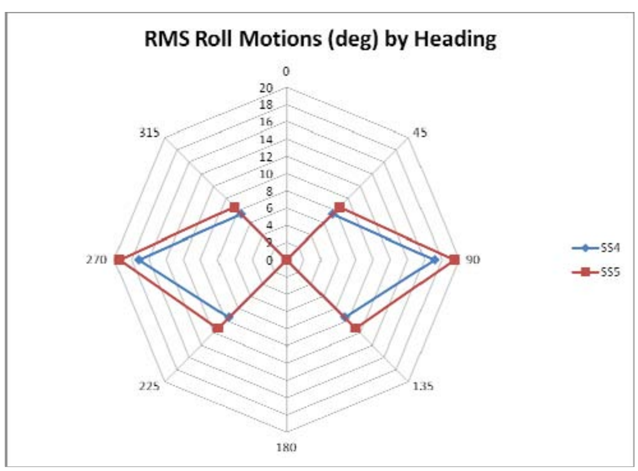


Figure 32: RMS Roll Motions by Heading

A combination of techniques was used to calculate vertical impact accelerations. The Hoggard-Jones method employed (Equation G-1) to estimate the 1/10th largest vertical accelerations at the vessel's LCG. These results were modified using (Equation G-2) to find accelerations representative of what the troops might experience [19].

Equation G-1: $$\eta_{cg,1/10} = 7.0\left(\frac{H_{1/3}}{B_{PX}}\right)\left(1+\frac{\tau}{2}\right)^{0.25}\left(\frac{Fn_v}{\left(L_{wl}/B_{PX}\right)^{1.25}}\right)$$

Equation G-2: $$\eta_{bow,1/10} = \eta_{cg,1/10}\left(1+\frac{3.8\left(L_{wl}/B_{PX}-2.25\right)}{V_k/\sqrt{L_{wl}}}\right)$$

Where:

$\eta_{cg,1/10}$ = largest 1/10th of vertical accelerations at LCG
$\eta_{bow,1/10}$ = largest 1/10th of vertical accelerations at bow
$H_{1/3}$ = Significant wave height (feet)
B_{PX} = Maximum Chine Beam (feet)
τ = Deadrise (degrees)
Fn_v = Volume Froude number ($Fn_v = v/\sqrt{g(\nabla)^{1/.3}}$)
L_{wl} = Length of water line (feet)
V_k = Velocity (knots)

Appendix H: Additional Renderings